
AC 2012-5413: EMBRACING THE PAST: USING HISTORICAL STRUCTURES TO TEACH ENGINEERING FUNDAMENTALS

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Embracing the Past:

Using Historical Structures to Teach Engineering Fundamentals

Abstract

The seminal structures of the 18th, 19th and 20th centuries, and the engineers who designed them, are important and fruitful topics for engineering education in the 21st century. By considering the social, political and economic context in which these structures were constructed, students will simultaneously be exposed to important themes in the humanities and social sciences, as well as practical engineering examples. In particular, these iconic structures are ideal vehicles for engaging students in rich discussions of the fundamental principles of statics, strength of materials, and structural behavior. Such inspiring examples are also highly motivational because they show the practical role that their current studies have in practice.

Introduction

Engineering students often come to their introductory classes wanting to know how big structures work. They are intrigued by bridges, skyscrapers, and long-span roofs. An excellent way to harness their curiosity and enthusiasm is to introduce them to both fundamental technical concepts and to the rich history of famous engineering structures. For example, the Eiffel tower is a vertical cantilever with a form designed to resist wind loads, an excellent focus for a discussion of statics. Gustave Eiffel and Maurice Koechlin determined the form of the tower using graphical methods. They did this after making careful assumptions about the distribution of wind forces on the tower and the effective surface area of the tower. (Figure 1)¹

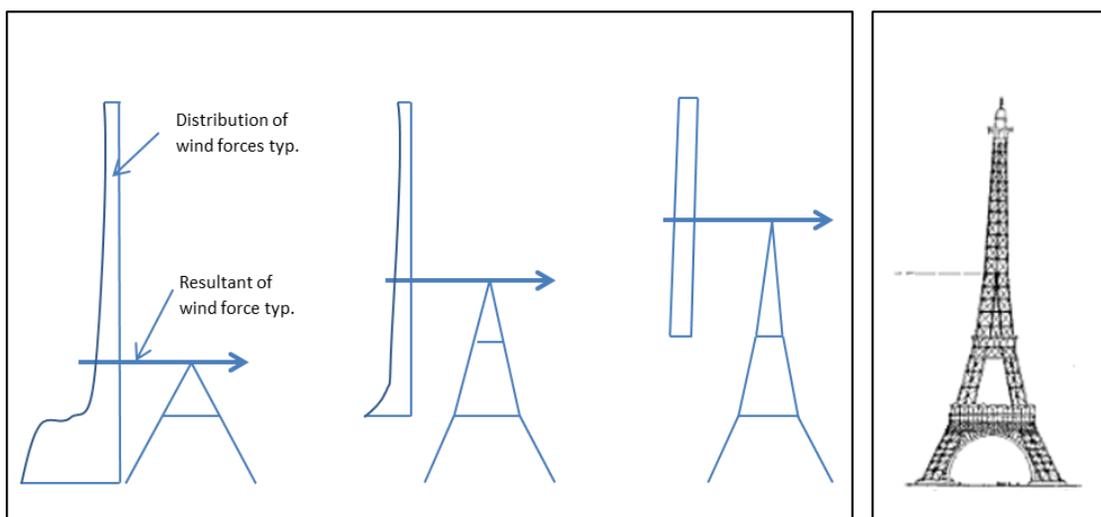


Figure 1. Schematic diagram of Koechlin's form finding methods...adopted from Allen.

In fact, graphical analysis methods are an ideal tool to reinforce fundamental concepts of structural form and behavior. Basic graphical techniques can be easily taught to both architecture and engineering students. Concrete arch bridges can also clearly demonstrate the relationship between form and force. Robert Maillart used graphical methods to determine the most efficient forms for his bridges. His most famous bridge, the three-hinged concrete box arch at Salginatobel, has tapering stiffening walls. The shape carefully responds to different critical live loadings. (Figure 2)

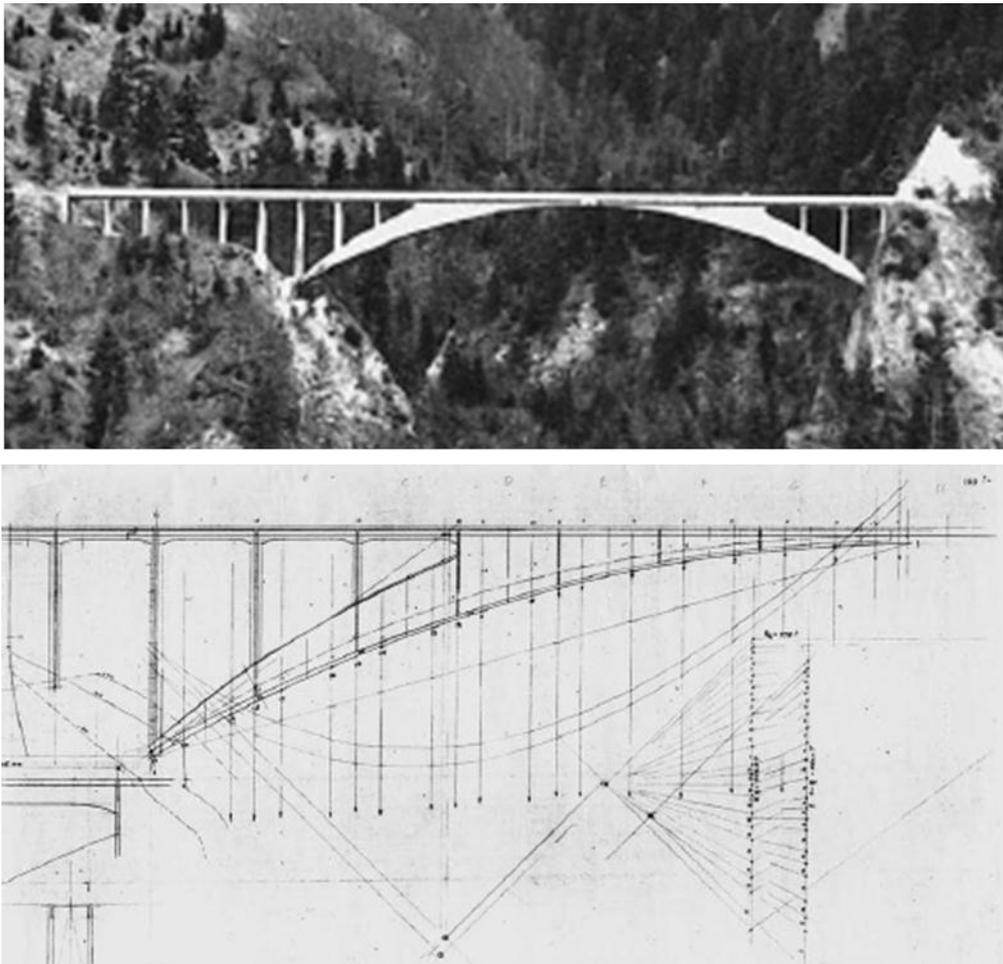


Figure 2. Salginatobel Bridge, 1929, by Robert Maillart, and a portion of his graphical solution.

Understanding these critical relationships between form and forces in structures is critical to achieving efficiency. The efficiency of all structures depends on the careful utilization of materials, an increasingly important design consideration. Young engineers need to learn the fundamentals of statics and strength of materials, and real buildings can reinforce these topics throughout their educations and beyond. The noted engineering author Henry Petroski has written eloquently about how important it is for the engineering profession to embrace its history. He argues that engineering history allows engineers to both understand and practice their craft. “Engineering history, in short, is engineering as well as history.”² The context in which great works of engineering are conceived, designed, and constructed is also important for

students to research and understand. Engineering students would be well served by studying the designers of important structures in addition to fundamental principles.

Iconic Structures

In 1965, the distinguished civil engineer Pier Luigi Nervi wrote thoughtfully in *Aesthetics and Technology in Building* about developing a student's "...static sense, the indispensable basis of intuition of structural imagination...". He was writing specifically about the education of architects, but this notion certainly applies to engineering students as well, and perhaps to anyone who designs building structures. He continues with the recommendation that students...

"...trace the development of structural schemes from ancient times up to the present, performing a static critique to show the relationships between the materials and construction procedures employed and the results achieved both from the technical and the aesthetic point of view."³

Engineering curricula include courses in statics, strength of materials, and dynamics, as well as steel, wood, and concrete design. There are excellent building examples in various materials and forms from several different historical periods that can be used as teaching tools in all these courses. Basic principles of statics, loads, load paths, and stability can be demonstrated with buildings ranging from roman arches and gothic cathedrals to steel frames and suspension bridges. Older structures tended to favor simple static schemes and forms which can be more clearly analyzed studied through diagramming and modeling exercises. Even the engineers of the massive Firth of Forth Rail Bridge, Sir John Fowler and Sir Benjamin Baker, demonstrated the basic principle of their cantilever design depicted in the famous photograph. (Figures 3 & 4)



Figure 3. Firth of Forth Rail Bridge, Scotland, Fowler and Baker, 1890.

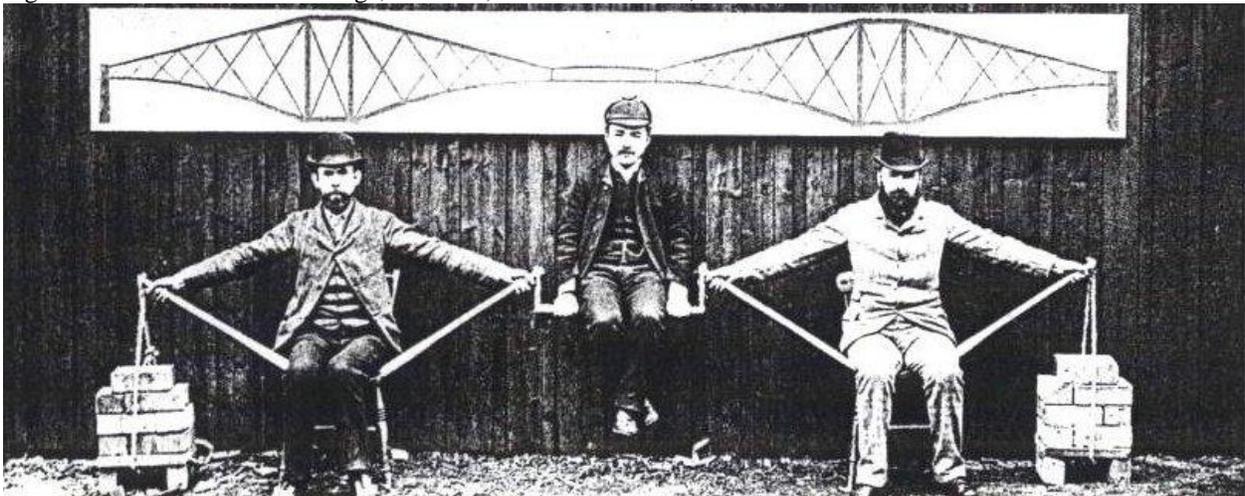


Figure 4. Iconic image of Sir John Fowler and Sir Benjamin Baker "supporting" the construction foreman Kaichi Watanabe, demonstrating the fundamental cantilever principle in their Firth of Forth Rail Bridge form 1890.

Industrial Revolution

The industrial revolution is a fertile period from which to draw outstanding examples of engineering design. As the new material iron was being developed as a structural building material, new building forms and longer spans were made possible. The corresponding expansion of railroad systems provided the demand for iron to be used in a wide variety of building applications. Bridges and train station roofs were common applications for early iron structures. These long-span structures are ideal forms for studying basic technical concepts such as equilibrium, stability, strength and rigidity. Bridges are especially suited to a discussion of structural principles since they are primarily load carrying devices whose designs are heavily influenced by the demands of efficiency. Arch and suspension bridges clearly display forms that work primarily in compression or tension. Many of these structures allow discussion of funicular forms as well. For example, students can investigate the effect of changing the curvature of an arch or suspension cable on the axial stress in the material using graphical methods.

Ironbridge (Figure 5) in Coalbrookdale England is a wonderful example of the early use of iron in bridges. Its form is interesting to note when comparing it to the masonry arch and wooden bridges that predate it, whose form Ironbridge mimics, as well as the flatter iron bridges that come after it. A valuable lesson is embedded here in the development of iron as a structural building material. As designers coped with using the new material, issues of construction and form were paramount. While the form of new iron structure at first closely resembled their predecessors, the capabilities of the new material began to be explored, both in overall form and in designing connection details and construction processes.⁴

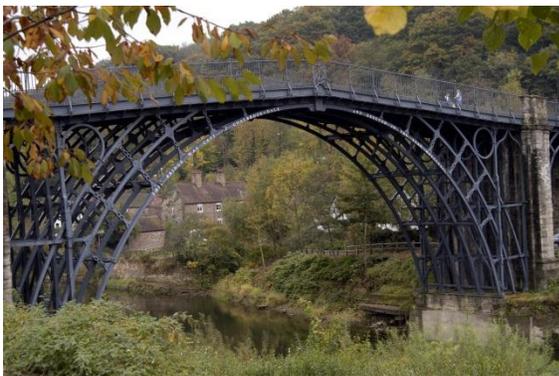


Figure 5. Ironbridge, Coalbrookdale England, Abraham Darby, 1779.

Other iconic structures to investigate include the works of Thomas Telford (Figure 6), a pioneer in the use of iron in bridge design. His career was closely intertwined with the development of iron as a building material during the industrial revolution. His arch and suspension bridge designs are clear examples of ways to use the new material. His iron bridges have flatter forms than their masonry counterparts, primarily due his recognition of iron's increased strength.

Many important bridges from that era are still in use today, including several long span suspension bridges that are iconic examples of the early use of iron in tension. Thomas Telford's 577 ft. span Menai Bridge (Figure 7), and his Conway Bridge, use overlapping iron bars

connected with solid pins to form the suspending chains. Basic connections stresses can be investigated in the “dog-bone” shaped iron bars: axial stress, shear stress, bearing stress, net section stress. These structures can also provide lessons on tributary area and load paths. Clifton Suspension Bridge by Isambard Kingdom Brunel is similar in style and design to Telford's suspension bridges. All three bridges use masonry towers to resist the compressive forces in the cables. These bridges are also ideal examples to study the funicular forms of the main “cables” or chains. Lessons on construction methods and stability in these early tensile structures are also possible.



Figure 6. Thomas Telford, 1757–1834



Figure 7. Menai Suspension Bridge, Anglesey, North Wales, 1925

Other building types to study with respect to emerging architectural and structural planning design challenges include framed structures. Two influential contributions to the use of iron as a framing system for architecture are the Bibliothèque Ste.-Genevieve in Paris (1850), and the Crystal Palace in London (1851).⁵ The pioneering design and construction features of the Crystal Palace are well documented, providing students with plentiful material to study this ground-breaking structure. Many structural planning and design issues, such as bay sizing, connections, lateral stability and cladding systems can be investigated and modeled. The concepts of prefabrication and assembly methods are also significant aspects of the Crystal Palace’s legacy.

20th Century Structural Art

The late 19th century saw the dramatic use of iron and steel for high-rise building construction in Chicago. William Lebaron Jenney, architect and engineer in Chicago and classmate of Eiffel’s at l’École Centrale des Arts et Manufactures in Paris, was instrumental in the development of iron and steel framed structures. His designs for tall buildings gave rise to the era of the modern skyscraper. Students can study this era to learn about multi-story construction, and early attempts at lateral stability systems. The historian, Carl Condit wrote extensively on the

American building and construction industry. His writings are an invaluable resource on various topics of interest to both engineers and architects.⁶

The dawn of the 20th century ushered in a new era of designers pioneering the use of reinforced concrete structures. David Billington, in *The Tower and the Bridge*, describes these engineers, who strove for efficiency, economy and elegance in their designs for large scale civic structures, as “structural artists”.⁷ Reinforced concrete arch bridges from the early 20th century are ideal for discussions of compressive force, funicular forms and axial stress. While studying these designers, who worked during the rise of the modern movement in architecture, engineering students will also be exposed to cultural and social issues affecting the design of large scale civil works projects. This was also a time in which graphic statics was commonly used to find good forms for structures and to determine member forces. The Swiss engineer, Robert Maillart, epitomized this way of working. (Figure 8)



Figure 8. Robert Maillart, 1872-1940

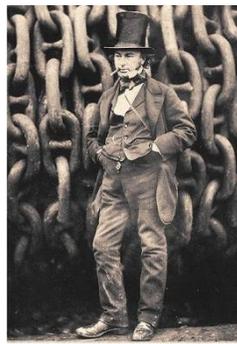


Figure 9. Isambard Kingdom Brunel, 1806-1859



Figure 10. Gustave Eiffel, 1832-1923

Engineering Personalities

The pioneering designers of historic structures, as well as many others, are also worthy subjects for engineering and architecture students to study. Thomas Telford, the grandfather of civil engineering was a prolific designer. As a mason, architect and engineer, he built roads, bridges, buildings, canals and harbors. He was an author and founding member and first president of the Institution of Civil Engineers, as well as a member of the Royal Society. He even wrote poetry, a sign of his classical training to compliment his self-training in technical and engineering subjects. Telford had a profound effect on the development of the civil engineering profession. His legacy is alive and well today in the numerous bridges and structures he designed and built, many of which are still in use and/or registered as historic landmarks. Telford’s masterpiece, the Menai Bridge, is often noted in discussions of deflection theory and suspension bridge aerodynamic stability that occurred after the collapse of the Tacoma Narrows Bridge in 1940. The Menai Bridge had experienced similar oscillations early in its life and the deck was damaged by gale wind storms on several occasions. The bridge deck had to be replaced several times, eventually with steel. Isambard Kingdom Brunel (Figure 9), as his stately name suggests, was also an influential 19th century engineer. Another prolific designer who only lived to age 53, he designed bridges, tunnels, railways, and giant steamships. Gustave Eiffel (Figure 10), best known for the 1000ft tall tower that bears his name also designed bridges and prefabricated metal buildings. Students could research how Eiffel experimented with iron structures in prior works such as the Viaduc de Garabit and the Maria Pia Bridge in Porto Portugal, and how those experiences contributed to his work on the tower.

In America, James Eads, designer of the record setting iron arch bridge at St. Louis, and John Washington, and Emily Roebling, designers/builders of the Brooklyn Bridge, are some of the important figures among early American engineers.

In addition to Robert Maillart, other influential early 20th century structural engineers include Eugene Freyssinet, Pier Luigi Nervi, Eduardo Torroja, Felix Candela, and Heinz Isler, all of whom worked with another “new” structural material; reinforced concrete.

There are many contemporary engineers for students to research as well. Designers such as Frei Otto, Christian Menn, Fazlur Kahn, Jorg Schlaich, William Baker and Laurent Ney. Several of these designers are practicing cutting edge structural engineering design today, and their work is widely published in technical journals. Their projects include the world’s tallest building, the Burj Kahlifia (Baker), long-span roofs for stadiums (Schlaich), and graceful pedestrian bridges (Ney).

Pedagogy

Another approach to studying historic structures should include lessons learned from engineering design mistakes and especially failures of buildings and bridges. Professional journals are filled with examples of failed structures. A student can learn important lessons from researching, writing, and presenting a paper on a significant collapse, especially the resulting changes in design methods and codes. Famous bridge disasters include the Quebec, Tay, and Tacoma Narrows bridges. More recent examples of building failures worth investigation are the Kemper and Hartford Civic center roof collapses. The Hyatt Kansas City walkway collapse is a great lesson in engineering ethics, as well as detail design, fabrication and construction. The story of William LeMessurier, the prominent structural engineer who reported a design flaw in his own skyscraper, the 59-story CitiCorp Center in New York City in 1978, is a compelling story of engineering ethics and professional responsibility.⁸

Conclusions

Engineering history can be taught as a course itself. However, utilizing iconic structures to teach engineering fundamentals would engage students in the rich history of technical developments, even as they are learning basic analytical techniques, much to the benefit of both subjects. Students quickly realize when studying iconic building examples that the technical concepts they are learning actually mean something. The motivational benefits of this approach are huge. It is the very nature of engineering progress to review what has been designed before when one is challenged to create a new engineering design. The rewards of using historical structures and researching their provenance will be many. Early structural designers tended to favor simple static schemes. It is just these types of statically logical structures, such as the Eiffel Tower and the Brooklyn Bridge, that lend themselves to lessons on form-finding, statics, and construction methods. Issues of loads, stress, and stability can also be discussed using bridges and early three-hinged arches. The development of steel and concrete as building materials resulted in structures that achieved strength and stability through means other than primarily relying on mass, expanding the quantity and type of structures available to study. The development of these new materials is naturally intertwined with social, political and economic changes of their eras.

Furthermore, engineering students would learn valuable lessons preparing a paper on the design process for a historic structure, especially from mistakes that were made along the way and how they were handled.

It is equally important and also rewarding to study the designers of influential structures. Many designers, including most of the designers mentioned already, left behind critical writings on engineering theory and design, a tradition which continues to this day. By drawing connections between eminent engineers of the past and some of today's practitioners, students can understand the role history plays in the evolution of buildings. By embracing the past, students are better prepared to carry on the legacies of the great designers. Students will gain an appreciation for the development of structures and structural design, as well as for the great engineers who created long spanning bridges or tall towers.

Bibliography

1. Allen, Edward and Waclaw Zalewski. *Form and Forces Designing Efficient Expressive Structures*. John Wiley and Sons Inc., Hoboken, New Jersey, 2010. pp. 286-288.
2. Petroski, Henry. *The Importance of Engineering History, International Engineering History and Heritage: Improving Bridges to ASCE's 150th Anniversary*. Jerry R. Rogers and Augustine J. Fredrich, editors. History Congress proceedings, American Society of Civil Engineers, Houston, Texas, October 2001, pp. 1-7.
3. Nervi, Pier Luigi. *Aesthetics and Technology in Building*. Harvard University Press, Cambridge, MA. 1965.
4. Peters, Tom F. *Historical Case Studies in System Thinking. A Pedagogical Tool for Teaching Construction Thought to Architects and Structural Engineers*. Proceedings of the Association of Collegiate Schools of Architecture European Conference, Copenhagen, 1996.
5. Trachtenberg, Marvin and Isabelle Hyman. *Architecture from Prehistory to Post-Modernism: The Western Tradition*, New York, Abrams, 2nd Ed, 2002.
6. Irish, Sharon, Editor. *Essays in Honor of Carl W. Condit*. Technology and Culture, The International Quarterly of the Society for the History of Technology. Volume 30. Number 2, April, 1989.
7. Billington, David P. *The Tower and the Bridge: The New Art of Structural Engineering*. Princeton University Press, Princeton, New Jersey, 1983.
8. Morgenstern, Joe. *The Fifty-Nine-Story Crisis*. The New Yorker, May 29, 1995, pp. 45-53.